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Novel Methods for Detecting Buried Explosive Devices

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Novel methods for detecting buried explosive devices

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ABSTRACT

Oak Ridge National Laboratory (ORNL) and Quantum Magnetics, Inc. (QM) are exploring novel landmine detection technologies. Technologies considered here include bioreporter bacteria, swept acoustic resonance, nuclear quadrupole resonance (NQR), and semiotic data fusion. Bioreporter bacteria look promising for third-world humanitarian applications; they are inexpensive, and deployment does not require high-tech methods. Swept acoustic resonance may be a useful adjunct to magnetometers in humanitarian demining. For military demining, NQR is a promising method for detecting explosive substances; of 50,000 substances that have been tested, none has an NQR signature that can be mistaken for RDX or TNT. For both military and commercial demining, sensor fusion entails two daunting tasks, identifying fusible features in both present-day and emerging technologies, and devising a fusion algorithm that runs in real-time on cheap hardware.

Preliminary research in these areas is encouraging. A bioreporter bacterium for TNT detection is under development. Investigation has just started in swept acoustic resonance as an approach to a cheap mine detector for humanitarian use. Real-time wavelet processing appears to be a key to extending NQR bomb detection into mine detection, including TNT-based mines. Recent discoveries in semiotics may be the breakthrough that will lead to a robust fused detection scheme.

KEYWORDS: quadrupole resonance, bioreporter, semiotic, landmine detection, wavelets, acoustic resonance

1. INTRODUCTION

Countermine has several different meanings. These different meanings define several distinctly different problems (military, humanitarian, commercial), with different tradeoffs and constraints. These problems demand several different (and not necessarily compatible) solutions, and have motivated several different courses of action.

Historically, the military countermine problem has motivated the most action. It is instructive to consider what the military says the problem is. The US Army's Communications and Electronics Command - Night Vision and Electronic Sensors Directorate (CECOM-NVESD) says that *the objective in countermine is secure unrestricted mobility for US forces.* Although mines may incidentally be detected and/or cleared in the process, neither of these is the objective; the specific objective of countermine operations is to minimize delay for forces transiting a mined area. The US Army's countermine efforts, going back at least as far as the first World War, have been specifically aimed at this objective.[1]

Recently, the humanitarian countermine problem has motivated the most discussion. The humanitarian problem derives from the fact that irregular forces use mine warfare primarily to terrorize civilian populations. The media are full of heart rending stories of maimed children in third world countries. The terror is fairly widespread; the oft-quoted statistic is that 80-110 million unexploded uncleared mines are lurking out there, waiting for their victims.[2] Several international Non-Government Organizations (NGO) with very sparse resources are making a limited effort to remove mines from civilian areas, but only about 100,000 per year are actually removed.[3] However, the primary response to the humanitarian countermine problem has been the attempt by well-meaning lawmakers to simply legislate the tens of millions of unexploded uncleared mines out of existence.[4]

Without much notice in the media, a new demining problem has emerged, mostly as a consequence of the Gulf War of 1990-91. This new problem is the commercial demining problem. Its distinction derives from the fact that while the victims are civilians, they are civilians with money. Nation-states and multinational corporations who are being denied access to needed resources are supporting

elaborate demining programs run by commercial contractors. The commercial approach uses elaborate arrays of multiple sensors, and very large computers to post-process the resulting torrent of data in search of mine signatures. Commercial deminers urgently desire a data fusion algorithm that would achieve two objectives, minimize the size of the sensor array without loss of information, and operate in real-time.

It is noteworthy that these problems are distinct. Military mine detectors must operate day or night, and must operate at high speed. Probability of detection (P_d) must be high, but not so high as to cause a high probability of false alarm (P_{fa}). High speed is not as crucial to in humanitarian demining, and the occasional false positive is tolerable. However, since it is performed by civilian contractors, P_d must be as near to 100% as possible.[5] Commercial deminers require extremely high P_d, low P_{fa}, off-the-shelf technology and high speed all at once. However, cost is a minor issue for their well-heeled clients.

Nevertheless the three problems have common threads. The objective of mine laying is to deny access, access of conventional military forces to desired positions, access of third world farmers to their fields, or access of sheikhs to their oil wells. For all three problems, trained dogs are effective mine detectors. However, the use of dogs is costly and presents enormous logistical problems.[3] Nobody is satisfied with present mine detection methods. For all individual sensors, the fundamental tradeoff is that a tolerably high P_d implies an intolerably high P_{fa}. Methods that work well in the laboratory do not work well in the real world.

The Defense Advanced Programs Research Agency (DARPA) characterizes the current state of mine detection technology with the observation that "breakthrough technologies are needed." Using the proposition that if dogs can find mines, then they are findable, DARPA argues that breakthroughs are realizable. However, breakthroughs will not be achieved by looking at the past and doing the same old things harder. To quote Sir Francis Bacon's sage advice, "If we are to achieve results never before accomplished, we must employ methods never before attempted."[3]

The countermine research efforts at Oak Ridge National Laboratory (ORNL) and Quantum Magnetics (QM) take their direction from this wisdom. A number of emerging technologies, not previously used for countermine problems, look promising. The authors are exploring solutions to the assorted problems of mine detection by using four completely unconventional approaches, bioreporter bacteria, swept acoustic resonance, nuclear quadrupole resonance (NQR), and semiotic data fusion.

2. BIOREPORTER BACTERIA

Is there a clever way to gain some of the advantages of canine detection while avoiding some of the costs? While it is not known specifically how the dog/handler team operates, it is clear that the dog detects a set of cues from the environment and "translates" them into another set of cues understandable to the handler. The dog's biosensors detect the presence of one or more cues and relay the message to its brain; the process somehow stimulates the dog to perform some set of responses that serve as cues to the handler that a landmine is present. It is fair to ask if there is not some other life form that could perform this same "translation" function less expensively and more conveniently than the dog.

One theory of canine mine detection presumes that olfaction is a key mechanism. The theory supposes that a mine emits trace amounts of its explosive, and that some fraction of these trace amounts find their way into the air near the landmine. From these trace amounts of explosive in the air, the dog sniffs a chemical signature, and then "translates" the information into a cue perceptible to humans. Genetically engineered bacteria can perform this same feat of "translation."

ORNL researchers are using such "translator" organisms for the detection of landmines and other buried ordnance. They have created bacterial strains that detect the presence of a specific chemical, such as TNT, and produce a signal that is easily detected. When the bacteria are in the presence of the explosive compound of interest, they glow. To produce the glow, both bioluminescence (the direct production of visible light by the bacterium) and fluorescence (a green glow in response to exposure to ultraviolet light) have been used in the laboratory.[6]

Bioluminescence comes from the lux genes. These are derived from a species of bacteria that lives commensally with several species of deep-sea fish. The bacteria produce visible light for the fish, which live in an otherwise dark world. It is hypothesized that the light is a lure for other fish, which are then snapped up by the host fish as a meal. This type of light production is familiar to anyone who has seen the light of fireflies, which use a different, though related, system to produce light. The lux system has proven to be very valuable in the past. However, the signal is relatively weak and requires sensitive equipment for detection when bacterial numbers are low.

Fluorescence is caused by the GFP (Green Fluorescent Protein) gene. GFP is a protein produced by a species of jellyfish that emits a green light on exposure to ultraviolet light. The advantage of this protein to the jellyfish is unknown. However, the GFP gene has been successfully isolated, and is available for cloning into other unrelated species. The fluorescence is particularly strong, and an individual bacterium emitting this signal can be seen under the microscope. The protein is also very stable, which allows the deminer a generous window of opportunity for finding fluorescent patches in a minefield.[7]

One advantage of GFP genes over lux genes is that the GFP fluorescence response can be switched on and off as the ultraviolet excitation light is switched on and off. Other sources of extraneous ambient illumination, such as moonlight, do not affect the switching procedure. Therefore, extraneous light can be easily distinguished from the fluorescence signal of interest.

The process of causing the bioreporter gene product to glow in response to the presence of specific chemical compound is referred to as expressing the gene. There are many mechanisms by which these genes might be expressed. The chemical may be a food source for the bacteria, and the genes are used to catabolize the chemical. The chemical may have a deleterious effect on the bacteria, and they respond with certain "stress genes" that mitigate the damage from the chemical. Several genes have been described which detoxify a chemical before the bacteria expels it from the cell.

These bacterial strains are not entirely naturally-occurring. Researchers select bacteria on the basis of their ability to respond to a certain chemical compound, and identify the gene that is responsive i.e. is induced. They then genetically modify the gene by fusing a bioreporter gene to it. The bioreporter gene encodes the proteins that create the signal. When the bacteria contact the target chemical the gene of interest is induced, along with the bioreporter gene, producing the signal (Figure 1).
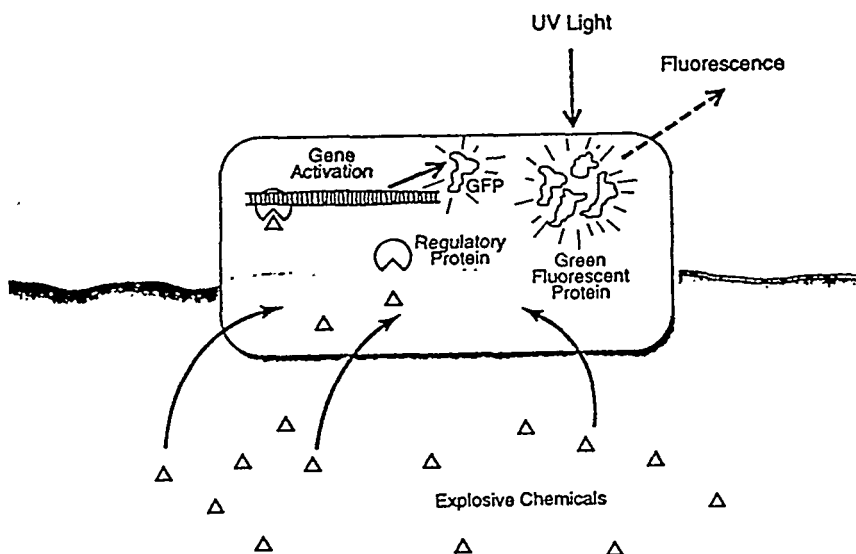

Figure 1. Genetically Engineered Bioreporter Bacterium

Since the bacterial strain is genetically engineered, the introduction of such a strain into the environment is regulated by Federal law. As experience grows with the application of these bacteria, such releases should become routine. However, at the present time such releases are rare and are always accompanied by intense scrutiny. ORNL was the site of the first release of a genetically engineered microorganism for the purpose of bioremediation, an experiment that is ongoing. ORNL has unique experience in the permitting required for such releases, particularly through the US. EPA Toxic Substance Control Act (TSCA) statute.

ORNL has created many such bacterial strains in the laboratory for the detection of hazardous waste compounds, such as naphthalene, toluene, and mercury. These bacterial clones are useful for the study of bacterial responses to contamination, particularly if bioremediation is being considered for the clean-up of a contaminated site. The fact that the responses of the bacteria can be viewed and quantified *in situ*, without disturbing the sample, is a tremendous advantage, since the sampling and analysis of bacterial communities can be time-consuming and costly.

Once the bacterial strain has been produced, the application of the technology for mine detection is straightforward (Figure 2). The bacteria can be grown by untrained people, using 55-gallon drums on the site of the minefield, and using technology that is both simple and inexpensive. Given the right nutrients and growth conditions, the bacteria will grow to high densities in a few hours. The bacteria are then sprayed over the area of interest. ORNL estimates that a coverage of 1000 bacteria per square cm is sufficient for detection of the fluorescent signal. A single 55-gallon drum should produce enough bacteria to be able to cover approximately 100 acres.
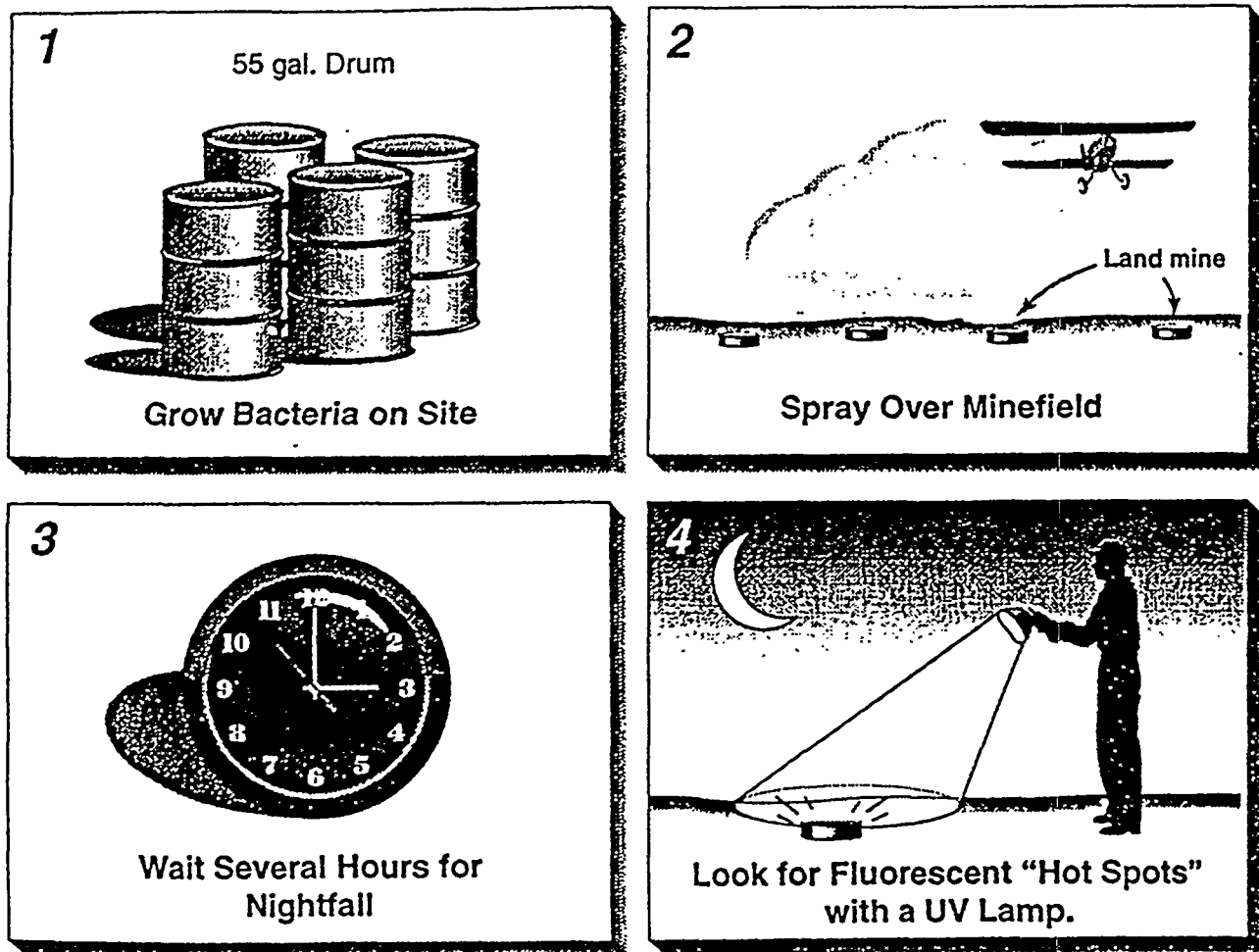

Figure 2. Application of Bioreporter Bacteria to Mine Detection

It is unlikely that this approach would be suitable for combat breeching of a recently laid minefield, but it is well suited to humanitarian clearing of old minefields, where the mines are more likely to leak and time is not as critical. After spraying the bacteria on the minefield, it requires several hours for the bacteria to contact the chemicals in the soil, express the genes, and produce the signal. The bacteria are detected by shining an ultraviolet light on the sprayed minefield, and looking for the green glowing patches. These are the aggregations of fluorescing bacteria on the surface of the ground over a buried landmine. These glowing patches are typically visible to the eye. However, for the sake of finding weak signals it might be desirable to use an electronic detector.

The major obstacle to the successful completion of this concept is the isolation of the appropriate gene, which must show an expression difference caused by the specific chemical. We have identified several candidate genes, the expression of which is induced in some cases, and others in which expression is repressed. Both types might be valuable. We are attempting to select the best candidate and demonstrate its properties under environmental conditions. The latter activity is very important, since activity in defined media conditions of the laboratory might not translate into activity out in the field.

3. SWEPT ACOUSTIC RESONANCE

The JASON Committee at MITRE Corp. was tasked by DARPA to investigate suitable technologies for humanitarian mine detection.[8] Swept acoustic resonance is one of the few technologies that the JASONs found to be promising for humanitarian mine detection. The JASONs also found that this technology is largely unexplored.

The idea suggested by the JASONs is straightforward. Mines have various structural features and hollow spaces that have mechanical resonances in the 5-50 kHz range. Since rocks, tree roots and the like have no hollow spaces, they do not have strong mechanical resonances as mines are expected to have. An incident broadband acoustic wave should cause a mine to vibrate at its resonant frequencies, but not impart enough energy to detonate, and have distinctive vibration signatures. This might provide the basis for a simple mine detector.

The objective of the swept acoustic resonance research just getting under way at ORNL is to take the JASON's suggestion and determine if it can provide an improvement to present procedures for humanitarian demining. Practically all the mines presently deployed, and the object of humanitarian mine detection, have some metal content. The problem is that the small metal content cannot be distinguished from other small objects such as spent bullets. The present practice is to detect the presence of metal with an AN/PSS-12 metal detector, and then probe with a short stick to identify the object.

A device based on acoustic signature might be a safer alternative to simply probing with a stick. The AN/PSS-12 can find the center of the location of the suspected object fairly precisely, and it can indicate other nearby spots in on either side of the suspected spot where there are no mines, and on which it is safe to place ground-contact ultrasonic transducers, one to send and the other to receive. The result is that the suspected object is between the transducers, and not in contact with either one.

This approach avoids the "standoff" problem, by not standing off. Using the information already available to the deminer, the transducers are in contact with the ground at safe spots. There is no "ground bounce," or the attenuation and ringing that go with it.

Also, this approach does not depend on reflection. It depends on the notion that a large class of mines will perturb the transfer function of the propagation path through soil in some repeatably detectable way. The objective of this research is to investigate whether or not this is so. The idea is that if the mine has internal mechanical resonances, this perturbation of the transfer function will be more pronounced than if resonances are not present.

The technical approach is based on the idea that a derivative Gaussian wavelet pulse of 32-microseconds support-length has its energy concentrated in the 5-50 kHz region (Figures 3 and 4). The pulse can be repeated at a 1 kHz repetition rate, and treated as repeated trials. A two-minute burst of such pulses constitutes 100K repeated trials. If 100K instances of the noisy received signal are averaged, a very low noise estimate of the received signal results. The denoised received signal can be decorrelated from the input wavelet to determine the transfer function of the propagation path. The resulting transfer functions will be investigated to see if there are consistent features that are present when there is a mine in the propagation path, and absent when there is no mine. If such features can be identified, they would serve as the basis to develop a cheap electronic feature extractor.
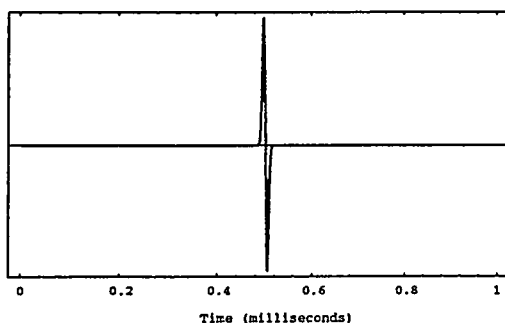

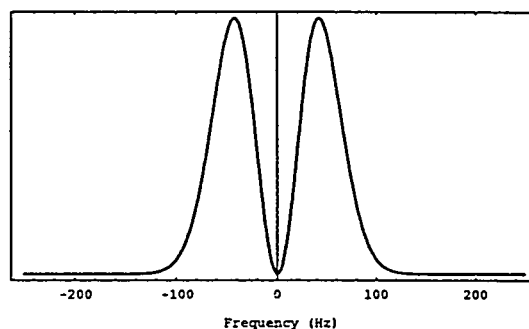
Figure 3. Derivative Gaussian Wavelet

Figure 4. Power Spectrum of Derivative Gaussian Wavelet

Thus, the device that might ultimately emerge from this research would work in concert with the AN/PSS-12, and is expected to be cheap, but too slow and awkward for military use. The AN/PSS-12 tells the deminer where a suspected target is and where to safely place the acoustic transducers. The acoustic device then provides a much better guess at to the identity of the suspected object than the information gathered from probing. More importantly, it would lead to a vast improvement in safety for the deminer.

4. NUCLEAR QUADRUPOLE RESONANCE

A straightforward approach to mine detection is to sense the high explosive directly. The one attribute that all mines have in common is that they do contain high explosive. Furthermore, whereas there are hundreds of different types of mines with many different attributes, such as varying sizes and shapes, there are fewer than a dozen popular explosives, of which only three, TNT, RDX and PETN are widely used.

However, until recently high explosives have been extremely difficult to detect. The quantity of explosive required for a bomb or mine is small. They can be molded into almost any shape, which defeats most projective techniques such as x-ray or neutron absorption or scattering. The very low vapor pressures and the impracticalities of coupling a sample into a detector make chemical sniffers an unattractive alternative. The cost and inconvenience of a powerful DC magnetic field render nuclear magnetic resonance (NMR) impractical outside the laboratory.

NQR overcomes these limitations. It can detect subkilogram quantities of explosive. NQR signature is independent of the shape of the explosive. The signature emanates directly from the condensed phase, and NQR is not bedeviled by the shortcomings that plague vapor-phase chemical detectors. NQR provides the chemical specificity of NMR and the volume capacity of magnetic resonance imaging without the need for expensive and cumbersome DC magnets.

The reason that NQR is not used as a general purpose analytical tool turns out to be exactly the same reason that makes it a good special purpose explosives detector. Only a few compounds (typically explosives) are constrained by their molecular structure such that they have a usable NQR signature. Over 50,000 compounds have been investigated, and none produce an NQR interference with RDX. Also, since only a few compounds have NQR signatures, false positive indications occur much less frequently than they do with activated neutron methods. Mines have NQR signatures; tree roots do not.

NQR exploits the electromagnetic interaction between atomic nuclei having a nonspherical electric charge distribution, and the internal electric fields due to the crystal structure in the condensed phase. For example, nitrogen nuclei experience a net torque leading them to precess about the local crystaline electric field gradient present in many explosive compounds. An externally applied radio frequency magnetic field pulse at the precession frequency generates a coherent, oscillating nuclear magnetic moment, which can be detected with a tuned antenna and very sensitive receiver.

An NQR explosives detector produces no hazardous emanations. The only emanation from an NQR explosives detector is low-powered low-frequency radio frequency (RF) energy. Power levels are typically on the order of tens of Watts. The most commonly used resonance for RDX occurs at 3.41 MHz. The NQR response of TNT is distributed over 12 spectral lines, with those most appropriate for mine detection in the band 836 kHz to 870 kHz.

Detection of RDX and PETN by NQR has been the subject of intense investigation by groups in the UK,[9] at the Naval Research Laboratory,[10] at QM,[11] and to a lesser extent in Russia.[12] In response to the Vietnam War, Bloch Engineering build an NQR-based mine detector capable of detecting 50 g of RDX at 20 cm in 12 seconds.[13] Under the same program R. A. Marino first measured the spectrum of TNT with high resolution.[14] Following the US approach, a group in the former USSR demonstrated a heavy but portable single sided NQR system for detecting RDX mines at 30 cm.[12] Most recently, a group in the UK demonstrated a single sided system for RDX with improved sensitivity over the Bloch work.[9]

However, the majority of recent work in NQR has been aimed at detecting explosives in airline luggage.[15,16,17,18] In the last year, fully automatic NQR systems to screen airline hold and cabin baggage have been successfully demonstrated at several major airports in the US and Europe. Technical improvments include: a significant increase in detection sensitivity, greatly reduced RF power used for the NQR excitation pulse, improved immunity to noise interference, and reduction of the system electronics to two plug-in PC boards.

A key breakthrough of particular relevence for mine detection has been the development of RF pulse sequences and hardware capable of greatly reducing the effect of magnetoacoustic and piezoelectric ringing, which has plagued previous work in ground scanning systems. A comparison of the NQR signals from free space, a variety of common materials typical of those found in the ground, and

RDX is shown in Figure 5. In particular, the negligible response from sand should be noted. Sand produces a very large piezo-electric ringing signal which has been largely indistinguishable from an true NQR explosives signal using prior embodiments of NQR technology.

Under two recent programs QM has reassessed NQR for mine detection in light of the latest developments, and potential future improvements in the core technology. Using current hardware and software a six turn spiral coil of inner diameter 10 cm and outerdiameter 25 cm and weighing 0.5 kg, was used to detect RDX at various distances from the plane of the coil. To simulate the conditions expected in field applications, the rms RF power used for the measurement was reduced to 20 W and the measurement time set to 1 second. The receiver operator characteristic (ROC) of 500g and 50 g of RDX at a distance of 15 cm and 6 cm respectively is plotted in Figure 6. For 90% probability of detection, the probability of false alarm is 0% for the larger sample and 5% for the smaller.
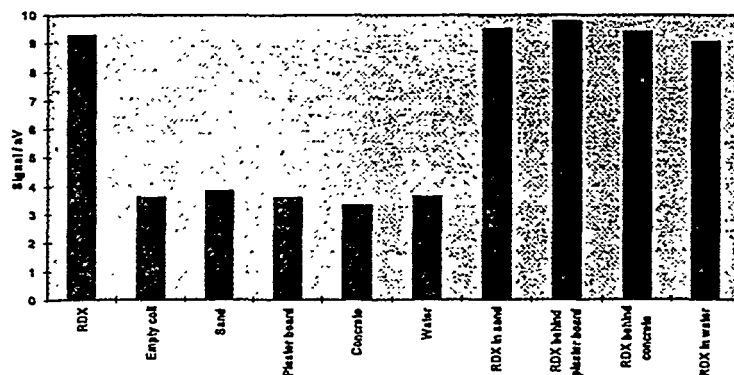

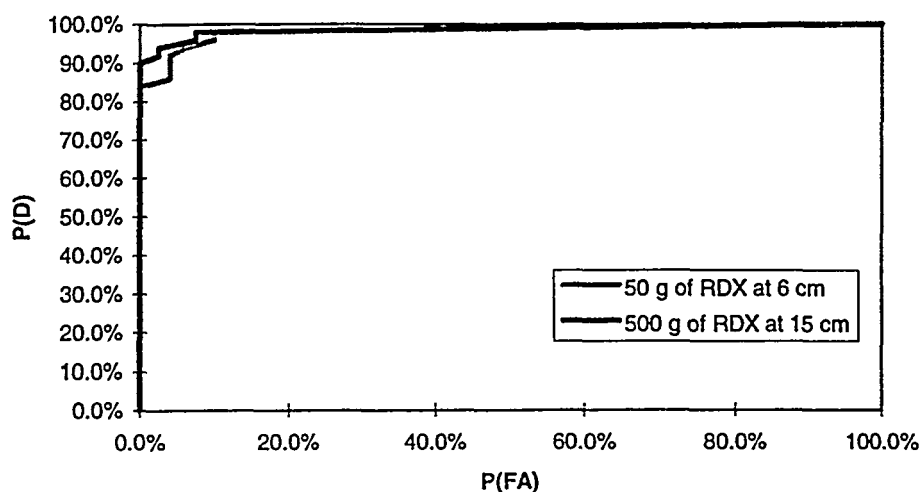Figure 5. NQR Responses to RDX and Concealing Substances

Figure 6. Receiver Operating Characteristic for NQR RDX Detector

Future advances in NQR for landmine detection require optimization and improvements of the new techniques and hardware for detecting TNT, and development of a lightweight single sided coil geometry tuned for both TNT and RDX. Using current techniques, TNT produces an NQR signal about as factor of five smaller than RDX. Several approaches are under development to increase the detectability of TNT including advanced signal processing and cryogenic preamplifiers. Initial calculations indicate that it should be possible to detect TNT with the same performance presently achieved for RDX with a man-portable system.

An advanced signal processing engine devised by ORNL, and based on the wavelet packet transform, appears to be capable of providing a performance edge needed to make NQR practical as a man-portable RDX/TNT detector.[19] The process provides simultaneous resolution of the signal in frequency and time. It shows promise for simultaneously reducing noise, distinguishing between NQR and acoustic ring responses, and simultaneously analyzing multiple spectral lines in parallel. The cascaded lattice synthesis of the wavelet packet can be implemented on a dedicated chip set.

In addition, sophisticated decision processes such as Bayesian hypothesis testing lead to highly reliable classification decisions. Furthermore, when a physical process is not well understood (for example, acoustic ringing), a Bayesian analysis is the most reliable method for devising an empirical description based on observed data. Also, whether from theoretical models or empirical descriptions, once a mathematical description of the relevant effects is obtained, it is possible to use Bayesian methods to derive a decision surface that can be rapidly implemented in real time, and gives assurance of the minimum probability of error.

5. SEMIOTIC DATA FUSION

Despite the profusion of sensor technologies being thrown at the problem, including the three already discussed in this paper, the fact remains that countermine sensor technology has simply not progressed to a satisfactory level. The JASONs captured the essence of the present state of countermine sensing in a quote from Colonel Robert Greenwalt, "Today, highly trained, scared soldiers use all their senses, augmented with a coin detector and a stick."[8] DARPA has an unambiguous criterion for the success of a mine detector. "When a soldier believes that a mine may be present - what does he reach for, a stick or your system?"[3]

CECOM-NVESD has not found any one sensing technology that will do the job, and sees the ultimate solution in the fusion of multiple sensors. Hanshaw has described the fusion problem in some detail, and discussed selection criteria for what technologies should be fused, but does not give any details of specific data fusion algorithms. A "thought experiment" describing how fusion operates is derived from considering how a soldier actually uses a metal detector. It is argued that the audible output of the sensor is "fused" with the operator's visual view of the scene and that the brain's cognitive power melds these cues into an awareness of the size and location of the mine. Furthermore, the process is adaptive; the skill at combining the visual cues with audible data improves with experience.[1]

Some of the specific elements needed to solve the fusion problem are reasonably well known. The problem in mine detection is "identity data fusion," and conventional data fusion methods address it with classic vector-based pattern recognition algorithms.[20] Data fusion systems reported in the countermine literature use conventional vector-based methods. Sometimes these are neural nets with orthogonal data streams.[1] Sometimes they are based on straightforward thresholding of vector quantities.[21]

The countermine literature draws a distinction between fusion and integration. Integration is the incorporation of several sensors as equals. Fusion is the merging of several different data streams of differing importance, into a state of awareness of whether or not a mine is present. Such a system would mimic animal reaction. Multi-sensor fusion is needed in order to simultaneously achieve high rates of detection and low false alarm rates, thus breaking the universal tradeoff that plagues single sensors.[1]

There is reason to believe that the multi-sensor data fusion problem is tractable. If dogs can consistently detect mines, then mines must have detectable features. Dog experts readily admit that they do not know how the dog does it, and it is not known how crucial olfaction is to the process. General Carl Stiner relates a story of one dog whose olfactory bulb had been surgically removed, but who could still detect mines successfully. Clearly, the dog was extracting non-olfactory features. Whatever form they may take, characterizing features exist and are identifiable.

Notwithstanding the argument that a consistent set of characterizing features exists, and notwithstanding the fact that many have tried to find it, nobody has ever found a vector space that characterizes mine identity. This strongly suggests that the features have not been found because researchers have been looking for the wrong thing. It is worth considering that dogs probably do not respond to mathematical number lists, but they almost certainly respond to semiotic structures.

Semiotics is the theory of signs and symbols. Traditionally, it is a branch of linguistics, and addresses the question of how the brain processes language. It is concerned with identifying the relationships between symbols, and extracting the meaning implied by both the symbols and their relationships. The value of semiotics is that it provides a theoretical justification for devising logically consistent methods for ferreting out the structures in a body of data. The semiotic structure is a non-vector characterizing feature. The essence of semiotic pattern recognition is the proposition that if two data sets have the same semiotic structure, then they belong to the same class, and if they have different semiotic structures, then they belong to different classes.[22]

The most relevant practical example of semiotic pattern recognition is Goldfarb's concept of the Inductive Learning Paradigm. He implements the concept with a mathematical structure called the Evolving Transformation System. The scheme is a semiotic-based unifying theory of pattern recognition in which classical structural methods, vector space systems, and even fuzzy logic all fall out as special cases. In the past, structural methods have had limited practical value, and vector methods attempt to learn bounds between classes in "feature vector space," but fail to reveal the structure of the data.[23]

In many cases, the structure, such as a string, a tree of strings, a tree of trees of strings, and so on, is the distinguishing feature. The Evolving Transformation System reveals the structure. However, it avoids the combinatorial explosion of conventional structural methods. Goldfarb shows that there does exist a practical way to measure the "distance" between abstract structures. This is akin to the much simpler concept of computing a norm to determine a "distance" (Mahalanobis, Euclidean, etc.) between vectors. In short, because it provides a computable way to reveal the characterizing structure, the algorithm may be the solution to many previously intractable pattern recognition (or data fusion) problems.

One such previously intractable problem might be the identification of mine signatures in cluttered multi-sensor data. To test the semiotic algorithm, field collection of new data would not be necessary. DARPA has recently collected a comprehensive and systematic set of experimental mine sensor data for a wide range of sensors and environmental conditions. Sensing technologies in the DARPA data set include ground penetrating radar, infrared, induction coils and magnetometers. The data were collected at Fort Carson CO, and Fort AP Hill VA. The sites were fully characterized. Weather, soil conditions, and temperature were monitored. In addition for the ground penetrating radar, dielectric conditions were monitored. The DARPA data set would provide a fair test of the semiotic algorithm.

As with mathematics, semiotics is the legacy of centuries of research. It has only recently been applied to the problems of artificial intelligence, and represents a radical departure from conventional practice. It shows particular promise for problems previously dismissed as intractable in the real world. It looks like an especially exciting approach to the mine data fusion problem.

6. CONCLUSIONS

As already noted, DARPA has an unambiguous criterion for the success of a mine detector. "When a soldier believes that a mine may be present - what does he reach for, a stick or your system?"[3] It is the specific objective of the authors to develop a set of technologies that the deminer (soldier or humanitarian) sees as safer and more reliable than a stick. Since most deminers prefer a stick to most conventional methods, it is necessary to investigate unconventional methods.

All the novel methods reported in this paper are presently being investigated by the authors for application to mine detection. Any or all of them may turn out to be practical breakthroughs. Bioreporter bacteria exploit the latest developments in genetic engineering to produce a mine detection scheme that may be ideal for third world humanitarian operations. Swept acoustic resonance may be a serious alternative to a stick, when used in concert with a metal detector. Recent breakthroughs in NQR physics, receiver design, and signal processing are expected to lead to a reliable instrument for man-portable detection of plastic mines. As an alternative to the "feature vector," the semiotic structure may prove to be the long-sought-after characterizing feature required for multi-sensor fusion.

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